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# TEM OBSERVATIONS OF Ti/AlNi/Au CONTACTS ON p-TYPE 4H-SiC (PREPRINT)


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**14. ABSTRACT**
Improved AlNi-based ohmic contacts to p-type 4H-SiC have been achieved using low energy ion ($Al^+$) implantation, the addition of a thin Ti layer, and a novel two-step implant activation anneal process. AlNi/Au contacts with and without Ti were studied, which resulted in contact resistivities around $1.8\times10^{-4}$ $\Omega$-cm$^2$ and $2.0\times10^{-3}$ $\Omega$-cm$^2$, respectively. Even though these values were higher than those of the Ti/AlNi/W system, which was the focus of previous studies, the reduced anneal temperature (650 to 700°C) implies that Ti/AlNi/Au is a promising composite configuration. Cross-sectional TEM and EDX were used to investigate the interfacial structure of these contacts. One possible mechanism for the improved ohmic contact behavior is that the addition of Au and Ti resulted in a reduction to the metal-semiconductor barrier height. These results have positive implications for developing lower temperature contact formation processes, which can minimize fabrication induced defects and enhance yield and reliability.

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# TEM Observations of Ti/AlNi/Au Contacts on p-Type 4H-SiC

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**Keywords:** SiC, Ohmic Contact, TEM, AFM, SEM, X-ray Diffraction, Specific Contact Resistivity

**Abstract.** Improved AlNi-based ohmic contacts to p-type 4H-SiC have been achieved using low energy ion ($Al^+$)implantation, the addition of a thin Ti layer, and a novel two-step implant activation anneal process. AlNi/Au contacts with and without Ti were studied, which resulted in contact resistivities around $1.8 \times 10^{-4}$ Ω-cm$^2$ and $2.0 \times 10^{-3}$ Ω-cm$^2$, respectively. Even though these values were higher than those of the Ti/AlNi/W system, which was the focus of previous studies, the reduced anneal temperature (650 to 700°C) implies that Ti/AlNi/Au is a promising composite configuration. Cross-sectional TEM and EDX were used to investigate the interfacial structure of these contacts. One possible mechanism for the improved ohmic contact behavior is that the addition of Au and Ti resulted in a reduction to the metal-semiconductor barrier height.

## Introduction

SiC is an excellent candidate for modern power electronics due to its superior breakdown voltage, thermal conductivity, and saturated electron velocity parameters, in addition to its inherent resistance to radiation and chemical attack [1]. A persistent problem plaguing SiC device development has been the realization of low-resistivity, thermally stable ohmic contacts to p-SiC. In previous experiments, improved thermal stability of the basic Al p-contact metallurgy was successfully demonstrated by using a binary AlNi compound [2, 3]. Tungsten was initially selected as a protective capping layer, and Ti was added (~40 nm) as an adhesion enhancing and resistivity reducing layer [4]. Gold was later chosen as the capping material to both prevent the oxidation of AlNi and to facilitate wire bonding to the contact. The primary goal of this current investigation was to correlate to the effects of Ti on specific resistivity and the overall morphology of the contact/SiC interface.

## Experiments

8° off-axis <0001> 4H SiC wafers with a 3 μm-thick, $N_a = 1 \times 10^{17}$ cm$^{-3}$ epilayer, were purchased from CREE, Inc. Degenerate doping of a thin surface region was accomplished using multiple energy/dose (80, 45, 24 keV / 5E15, 2E15, 1.2E15 cm$^{-2}$, respectively) $Al^+$ implantation at 650°C. SIMS analysis of the ~ 0.3 μm implanted layer was conducted to verify the profile and desired atomic concentration of $>10^{20}$ cm$^{-3}$. The implanted surfaces were capped with pyrolized photoresist, then the wafers were subjected to a two-step activation anneal at 1400°C then 1700°C for 15 minutes at each temperature. After anneal, the graphite was removed using dynamic oxygen flow in a quartz tube furnace for several hours. TLM patterns on mesa structures were prepared as described previously [2, 3]. The metal stacks were then deposited by rf magnetron sputtering, resulting in the following composite metallization scheme: ~40 nm Ti as the first layer, followed by ~200 nm AlNi, and a third layer consisting of ~100 nm Au. Post deposition anneals for this set of samples were carried out in the temperature range of 600$^o$C to 750°C for 30 minutes in a high purity Ar atmosphere with a heated Zr-tube gas purification system. Subsequently, a set of samples without Ti was prepared and heat treated using the same procedure mentioned above. Current-voltage (I-V) measurements were performed at room temperature between heating cycles for each set of samples. Representative samples were selected from each sample set before and after anneal,

and TEM cross sectional specimens were prepared using a Focused Ion Beam (FIB) technique. After completion of all electrical measurements, the samples were wet-etched using a HF: $HNO_3$: $H_2O_2$ (5:5:1) solution to remove the contact patterns and expose the interface between the contact and SiC substrate. AFM, SEM, TEM, EDX and XRD analyses were conducted on samples of particular interest.

## Results and Discussion

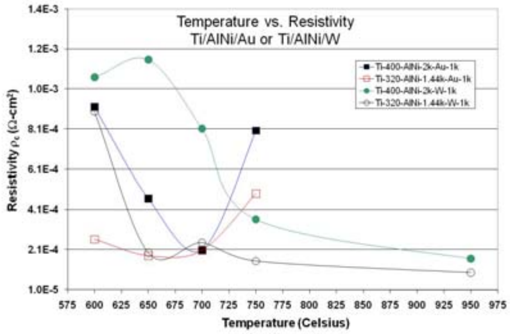


**Fig.1** The effect of anneal temperatures on specific contact resistivity

Figure 1 summarizes the effect of anneal temperature on the specific contact resistivity of both Ti/AlNi/Au and our standard Ti/AlNi/W metallization. This confirms that an anneal temperature between 650 and 700°C for 30 minutes is sufficient to obtain ohmic characteristics for the Au capped samples, and is significantly lower when compared to the annealing temperature required for resistivity optimization of Ti/AlNi/W contacts. As seen in the figure, the Ti/AlNi/Au samples resulted in contact resistivities as low as $1.8\text{x}10^{-4}$ $\Omega$-cm$^2$. Under the same conditions, however, the resistivity of the AlNi/Au contacts was only on the order of $2.0\text{x}10^{-3}$ $\Omega$-cm$^2$. Figure 2 shows pre-anneal X-ray mapping images (8 hour acquisitions, including drift correction), a TEM micrograph, and EDX chemical analysis data for the Ti/AlNi/Au sample. As seen in this figure, the Ti, AlNi, and Au layers are readily distinguishable. Figure 3 depicts the effects of a 700$^o$C, 30 minute anneal, revealing significant interdiffusion of the composite layers. Comparing the two sets of EDX data, it is seen that Au has diffuses toward the substrate, while the AlNi layer is displaced upward. The Ti is seen to have diffused through the structure. This agrees with the contrast differences observed between the two TEM images. Figure 4 shows TEM images of Au/AlNi/SiC before and after anneal revealing no distinguishable diffusion between the AlNi and SiC. Figure 5 shows SEM images of the Au/AlNi/Ti/SiC and Au/AlNi/SiC surfaces after wet etching. The SEM micrograph indicates extensive reaction between contact containing Ti and the SiC surface layers. AFM scans highlighting the difference in surface morphology between the two samples after contact removal are shown in Figure 6. The average roughness of the exposed contact area is 5 nm for the sample with Ti and 1 nm without Ti. These observations are supported by XRD results, which indicate the formation of TiC, $TiSi_2$ as well as several Au-Al compounds. High resolution TEM analysis is currently underway to investigate lattice images of the interface. The exact role the TiC and $TSi_2$ play in ohmic contact performance is still unclear at this time; however, the contribution of Au may be quantifiable. That is, the specific contact resistance $R_C$ for contacts with a high doping level, ~$10^{20}$ cm$^{-3}$ in this case, is approximated by $R_C \sim \exp\{c^*\phi_{bn}/(N_D)^{½}\}$, where $\phi_{bn}$ is barrier height, c* is constant, and $N_D$ is donor impurity density. For $N_D \geq 10^{19}$ cm$^{-3}$, transport is assumed dominated by tunneling , and $R_C$ decreases rapidly with increased doping [5]. Since the doping level was the same for all the samples, the improved ohmic contact behavior noticed in this study may be attributed to a reduction in barrier height due to the addition of Au. This reduction in barrier height was explained using a model with an enhanced electrical field at the interface due to the small size of the Au particles and the large difference in barrier heights between Ti and Au on SiC [6]. The Schottky Barrier Height (SBH) of Ti/SiC is 2.26 eV and the addition of Au particles reduces the SBH to 1.94 eV [6].

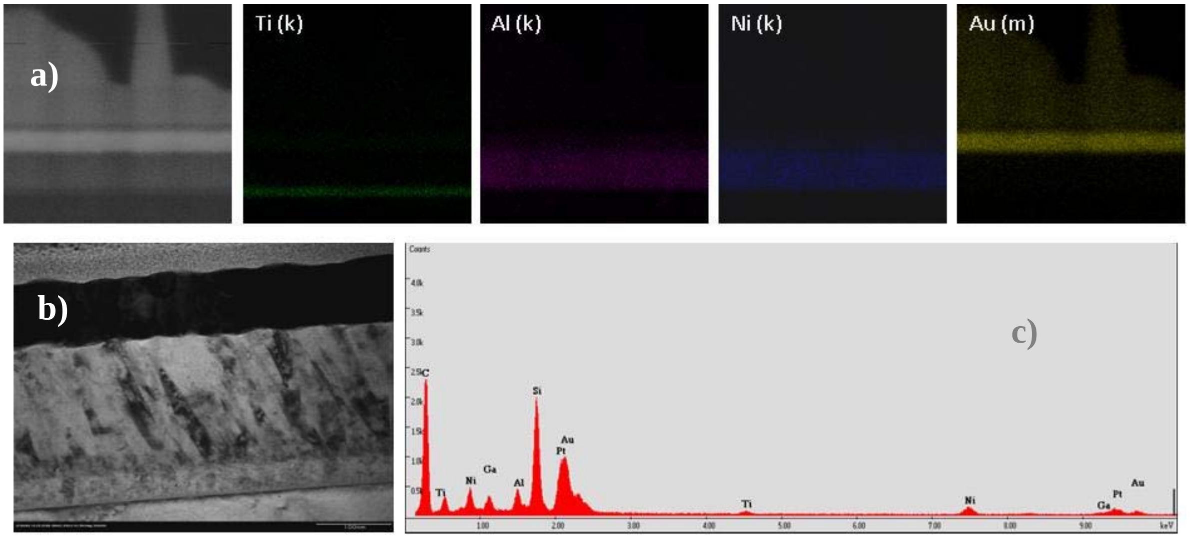


Fig.2 a) X-ray mapping b) TEM micrograph C) EDX spectrum of Au/AlNi/Ti/SiC sample before anneal.

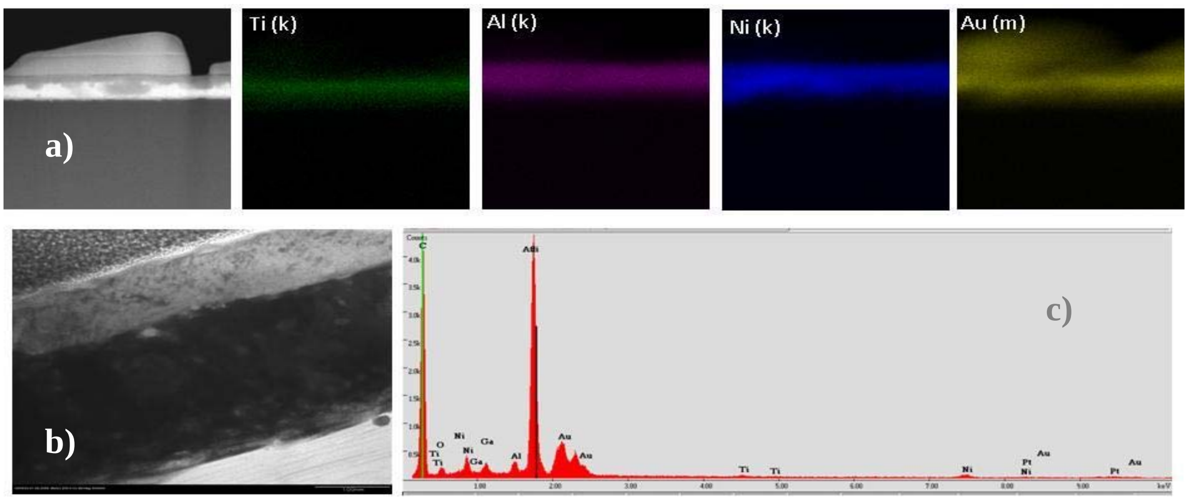


Fig.3 a) X-ray mapping b) TEM micrograph C) EDX spectrum of the Au/AlNi/Ti/SiC sample after anneal.

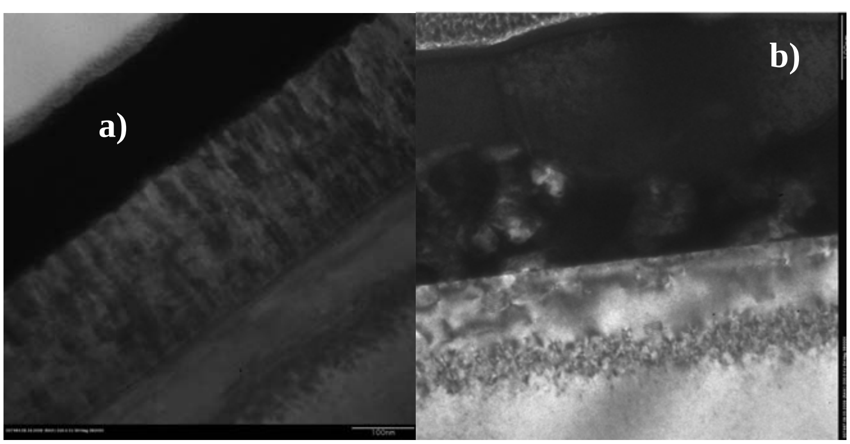


Fig.4 TEM micrograph of the AlNi/Au/SiC sample a) before and b) after anneal.

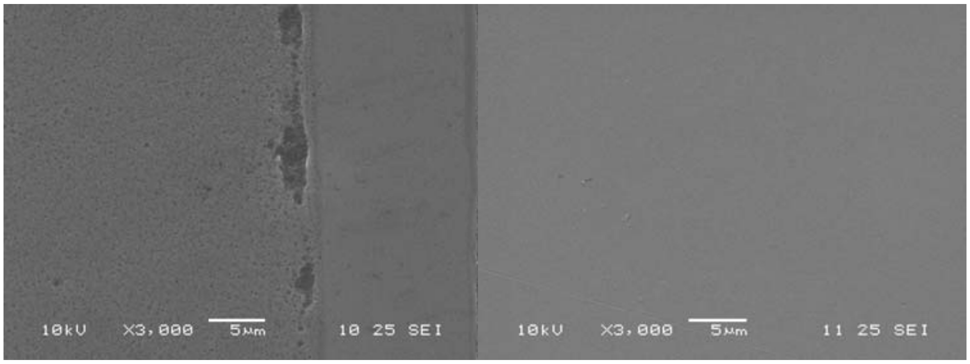


**Fig. 5** SEM image after wet etching of the (a)Au/AlNi/Ti/SiC, and (b) Au/AlNi//SiC sample.

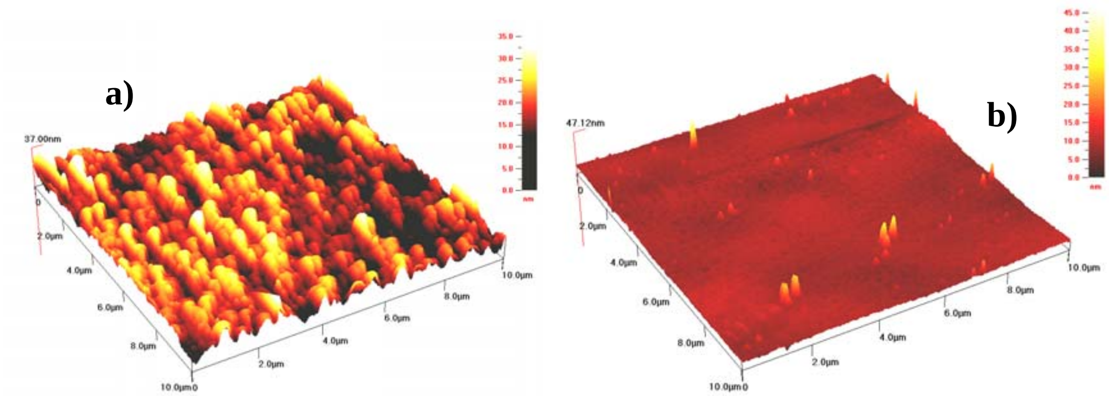


**Fig. 6** AFM scans of the exposed contact areas of the a) Au/AlNi/Ti/SiC and b) Au/AlNi//SiC samples.

## Summary

A lower contact resistivity was noticed for the Au/AlNi/Ti/SiC in comparison to the Au/AlNi//SiC sample. TEM observations show that Au tends to diffuse toward the interface boundary of Ti and SiC. This Au diffusion possibly resulted in a reduction to the metal-SiC barrier height. Though their presence was confirmed, the exact role that TiC and $TiSi_2$ play in ohmic contact performance is still unclear. It may be concluded, however, that the addition Ti improves adhesion between the AlNi and SiC, perhaps through the formation of these compounds.

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## References

[1] R.F. Davis et al.: Materials Science and Engineering, **B1**, 77 (1988).
[2] S. Liu, B.-H. Tsao, and J Scofield: Proc. 6th Int'l High Temp. Elect. Conf., (2002).
[3] B.-H. Tsao, J. Lawson, and J Scofield: Proc. ICSCRM 2005.
[4] J. Crofton, L.Beyer, J. Williams, E. Luckowski, and J. DeLucca: Solid State Electronics, **41**, No 11, 1725(1997).
[5] S. M. Sze,: Semiconductor Devices Physics and Technology, Wiley(1985).
[6] S.-K. Lee, et.al: Solid State Electronics, 4**6**, 1433(2002).